Short Course on Experimental Dynamic Substructuring

Module #05: Measurements make or break your experimental model

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Short Course Notes For:
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Bad measurements ruin experimental models

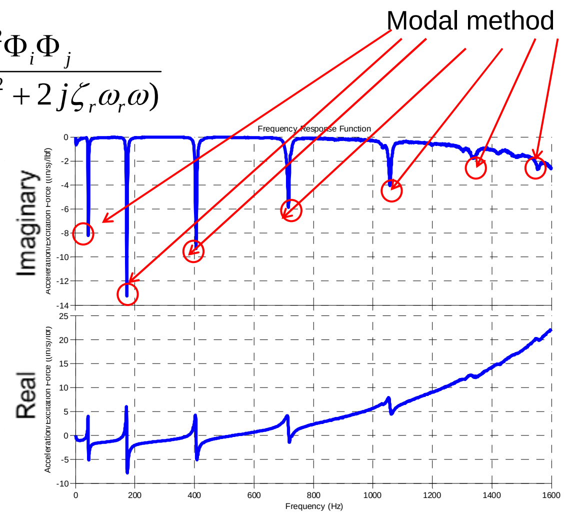
Measurement details addressed here

- Response sensor measurement errors and their sources
- The most critical sensor locations
- Checks for validating your critical sensor responses
- Placing sensors to minimize theoretical errors
- Force sensor measurement errors and their sources

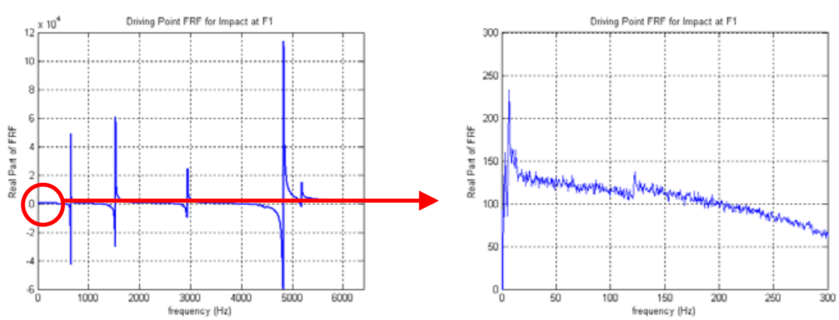
Response sensor measurement errors/error sources

- Experimental substructures require MUCH more accurate measurements than model validation modal parameters

$$H_{ij}(\omega) = \sum_r \frac{-\omega^2 \Phi_i \Phi_j}{m_r(\omega_r^2 - \omega^2 + 2j\zeta_r\omega_r\omega)}$$



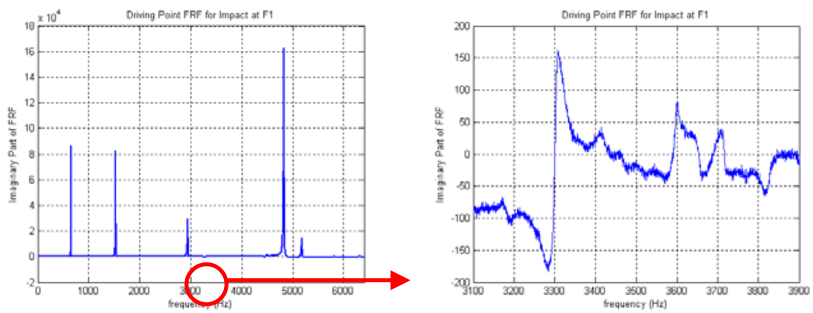
FRF substructure measurement demands



Real component of FRF must be accurate to get correct combined system resonant frequencies

- First glance, data “looks good”
- Closer examination, low S/N ratio
- When combining substructures this noise can cause wrong resonant frequency

FRF substructure measurement demands



Imaginary component of FRF must be accurate to get correct combined system resonant amplitudes

- First glance, data “looks good”
- Closer examination, noise present, data oscillates about 0 (imaginary drive point should always be POSITIVE)
- When combining substructures, this noise can result in wrong sign and amplitude

Response sensor measurement errors/error sources

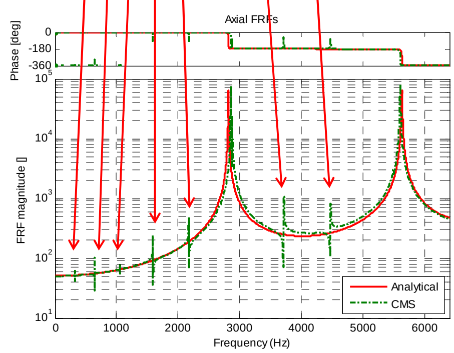
- Common sources of error (approximately ranked)

1. Bookkeeping errors (wrong sign, wrong dof, crossed wires, wrong sensitivity/gain, local coordinate system errors)
   - Administrative double checks (multiple people) on mounting, channel table, coordinate system definition
2. Choosing too wide a bandwidth (in general the difficulty of developing an accurate experimental model increases with frequency)
   - Minimize your bandwidth as much as possible to meet the requirement – push back when people ask for the moon
3. Undetected overloads (driving the sensor, amplifier or DAQ hardware beyond rated ranges ruin or pollute the data, but the digital anti-aliasing filter makes it look just fine)
   - Set bandwidth wide open and collect some at-level data to verify that you are not overloading sensors or signal conditioning

Response sensor measurement errors/error sources

- Common sources of error continued (approximately ranked)

4. Cross-axis sensitivity
   - For very lightly damped systems, modes have the apparent real part and imaginary part switched (i.e. peaks in the real part of the acceleration FRF instead of in the imaginary part). Not easily fixed

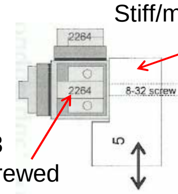


Response sensor measurement errors/error sources

These compete

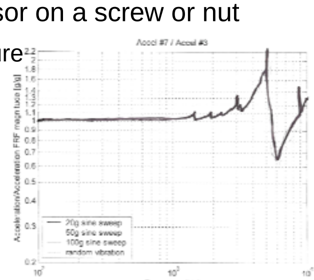
5. Base strain sensitivity in which strain in the accelerometer causes response (often observed with large uncharacteristic low frequency response in FRF)
   - Place the accelerometer (preferably) on a block or (less preferably) on tape with adhesive layer
6. Mounting resonances or mounting block resonances
   - At some frequency, tape mounted accels see phase shift, and block mounted accels will have a mode of the block mass oscillating locally on the structure.
   - Beware if you mount a sensor on a screw or nut

Stiff/massive fixture



15.9 mm^3 Block – screwed and glued

$\ddot{x}$



Response sensor measurement errors/error sources

7. Dead sensors or sensors with wrong amplitude
   - For near free-free systems, extract a low frequency (off resonance) operating shape in each of three orthogonal directions to be sure all gages have reasonable amplitude (this also helps diagnose bookkeeping errors)

The most critical sensor locations

- The sensors used for connection to another substructure are by far the most critical (they are used in the inversion in FRF substructuring and pseudoinverse of mode shapes of the transmission simulator)
  - The most critical of the critical are the drive point sensors
    - For direct FRF modeling, all connection dof are drive point FRFs
    - For modal modeling or FRF modeling derived from modal parameters, only a relatively few key drive points must be used
      - If using a transmission simulator fixture, a FE model of the fixture can guide one in selecting good drive points to excite all modes up to certain frequency (Rule of thumb, all modes should be excited at locations with a mode shape coefficient at least 0.5 times the maximum mode shape coefficient for that particular mode)
    - Drive point measurements require logistical consideration for applying the force as well as measuring the response

The most critical sensor locations

- Every connection dof should be, at least, approximated in the model
  - This is extremely difficult when using the physical connections
  - The transmission simulator (MCFS) method and the CPT method capture the modal dof which can be related to every connection point translation and rotation through a modal transformation. This even works for continuous connections. Truncation errors arise when the true connection motion goes beyond the mode shape space used for the transmission simulator, but approximations are much better than DELETIONS

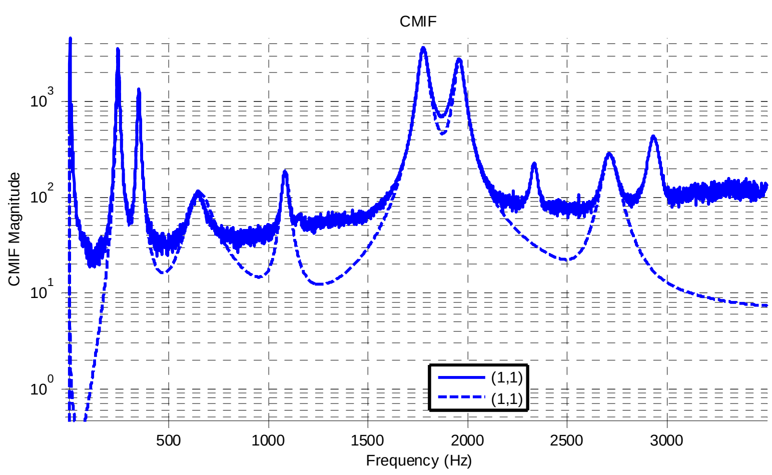
Checks for validating the most critical sensor responses

- If one is performing a free-free test (our recommendation), the most important modes are the rigid body modes, and those must be estimated accurately
- Compare the experimental low frequency mass lines of every drive point with the analytical mass line (works for both modal and FRF based substructures).
  - This can uncover bookkeeping, sensitivity, base strain and other measurement errors.
  - One must know the mass, center of gravity and moments of inertia to get the rigid body mode shapes.
  - From the rigid body mode shapes one can generate drive point FRFs with the low frequency mass line for each substructure.
  - Also, one can compare the low frequency mass lines of the combined substructures with the analytical low frequency mass lines of the entire system. If the low frequency mass lines are significantly in error, there is something wrong with the substructuring process or models. Rigid body substructuring should always work (i.e. no singularities, etc.)

Checks for validating the most critical sensor responses - continued

- If one is performing modal substructuring, compare the FRFs synthesized from modal parameters to the test data for the substructure.
  - Data should compare “well”
  - Pay particular attention to FRFs from other references besides the one from which the modal parameters were obtained. Errors in these show modal scaling (modal mass)errors. Both mode shapes and modal mass must be accurate. Note that damping errors will be over-compensated for in mode shape errors.
  - A good first check is to compare the complex mode indicator functions from the actual test data from all inputs and the synthesized modal parameters (especially the imaginary part) – see the next page for example CMIF

Checks for validating the most critical sensor responses - continued

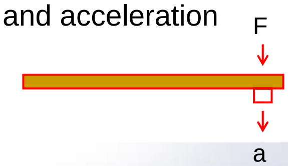


Placing sensors to minimize theoretical errors

- The transmission simulator method is very amenable to analysis if one has a FE model of the transmission simulator (which is used to establish all the connection motion / equilibrium)
  - Number of sensors – Use at least 1.5 times the number of modes of the fixture in your bandwidth of interest (rule of thumb)
  - Pick a large number (3 to 10 times the no of sensors required) of candidate locations that can actually be instrumented
    - For modal substructuring, several of these must also be at locations where one may apply force for drive point
    - For FRF substructuring, ALL candidates must be at a location where one may apply a force
  - Use an algorithm for choosing connection sensor dof that allows the mode shape matrix of the final sensor set to be easily inverted with pseudo-inverse (condition number ~3.5)
    - Algorithms that minimize condition number of TS mode shape matrix
    - Effective independence (Kammer) or Min-Mac (Carne, IMAC XIII)
    - Sensors don't have to be at actual connection points and can be only translations!

Force sensor measurement errors and their sources

- As stated earlier, the drive point measurements are the most important – errors in these measurement amplitudes can ruin the connection process because the mass is directly derived from the ratio of F/a.
- The force is assumed to be co-located with the drive point response accelerometer. Often this can be approximated for lower frequencies with a co-linear force and acceleration



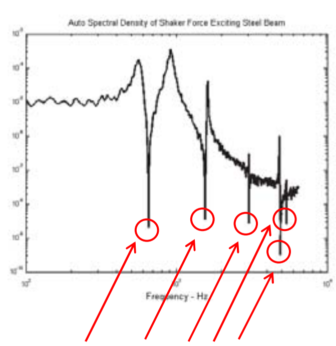
- Special features should be available in the transmission simulator to allow co-linear force and acceleration measurements at critical drive points (e.g. radial caps, tangential blocks or stubs)

Force sensor measurement errors and their sources – Shaker vs. Hammer

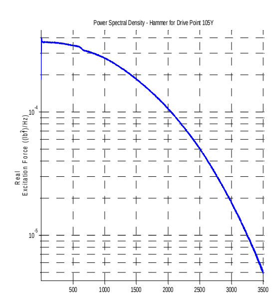
- A shaker can produce a more linear result and better signal to noise ratio for same peak force on a non-linear system (using random with Hann window)
- A hammer can provide much higher frequency data
  - Shakers uncouple above armature resonance
  - Shakers have stinger and shaker lateral/rotational dynamics which pollute the axial force being measured at higher frequencies and can actually give false modes
  - Force gages add axial, lateral and rotational mass that is not accounted for in the measurement (Have seen mass pollution that shifted frequencies up to 10% on one substructure!)
- A shaker has more precise input location/direction/amplitude
  - A hand held hammer strike can provide some unwanted shear input as well as normal
  - Pendulum fixtures for hammers can improve this over hand held hammer strikes
  - Factory calibration on hammer sensitivity +/- 15% vs force gage(+/-) 5% or better

Force sensor measurement errors and their sources – Shaker vs. Hammer - continued

- A hammer provides strong input at the resonances whereas uncontrolled shaker input will drop drastically in force at the resonance (especially for lightly damped structures)



Force drops at resonances in autospectrum of shaker



Autospectrum of hammer impact